RELATIONSHIP OF TEMPERATURES TO BOLL WEEVIL COMPLEX POPULATIONS IN ARIZONA

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RELATIONSHIP OF TEMPERATURES TO BOLL WEEVIL COMPLEX POPULATIONS IN ARIZONA

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SUMMARY

The major factor affecting the boll weevil complex (*Anthonomus grandis* Boheman) in Arizona is temperature. The development and mortality of individual weevils as well as the entire population are directly associated with the temperature in the oviposition sites and on the soil surface and indirectly with the heat input resulting in maturation of cotton plants. Individual weevil development, the population fecundity, longevity, and mortality, and the maturing of cotton plants may be estimated with equations. These were developed with least squares analysis from several untransformed forms of cubic and quadratic, transformed forms of cubic and quadratic, the Fourier series, asymptotic, and logarithmic models. The equations accurately describe the relationship of the several phenomena with time or heat input.

The boll weevils are suppressed by high temperatures during June, July, and frequently August, but their population increases as cooler fall temperatures ensue and the early maturing cotton bolls release an accumulated population of boll weevils to oviposit in late fruit.

INTRODUCTION

Various aspects of the history, biology, and ecology of the boll weevil complex[2] in Arizona have been reported (Fye *2–5*, Fye and Leggett *10*, Fye et al. *11–12*, and Leggett and Fye *14*).[3] Likewise, studies of temperature in the various cotton-field environments have been published (Bonham and Fye *1*, Fye *6*, and Fye and Bonham *7–9*).

The development of equations in this report will serve to integrate several of these facets and introduce others not previously considered.

The flowsheet for the development (DS and DB series) and mortality (MS and MB series) aspects of the boll weevil life history in cotton squares (S series) and bolls (B series) is presented as figure 1.

METHODS

Adult Female Population Assessment.—The first essential assessment in studying the population dynamics of the boll weevil must be made when cotton squares become available for oviposition sites. The operating characteristic curve (Kuehl and Foster *13*) places confidence limits on mean population densities by utilizing probabilities associated with known sampling distributions of the insects. It lends itself to such an assessment. The technique, now under modification for use with cotton insect populations,[4] employs the number of samples taken and the number of insects found in the samples to determine the proper probability for estimating the confidence limits.

The use of the operating characteristic curve or any other intensive sampling system to determine the original ovipositing population will suffice; however, a knowledge of the confidence limits associated with a mean population density is highly desirable.

Eggs Laid in Squares and Bolls.—During boll weevil surveys in 1965 and 1966 in Arizona (Fye *2*), the egg punctures of the weevils were recorded as being either in squares or in bolls. Generally the infestations were light and no pattern

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[2] *Anthonomus grandis* Boheman; Curculionidae: Coleoptera.

[3] Italic numbers in parentheses refer to Literature Cited, p. 13.

[4] R. O. Kuehl, statistician, Arizona Agricultural Experiment Station, personal communication.

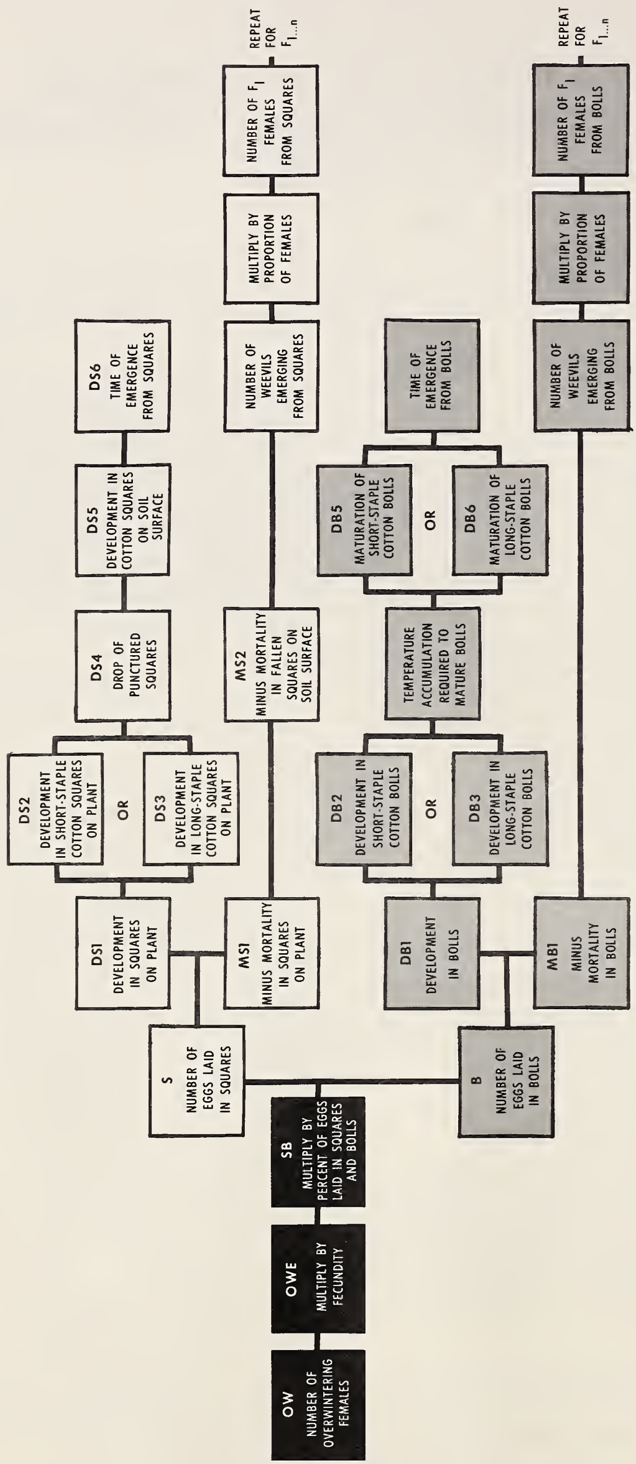

FIGURE 1.—Flowsheet for development and mortality of boll weevil in Arizona.

could be established. However, the 1965 data included 13 selected fields with adequate populations to allow consolidation and approximation of the percent of eggs laid in squares and in bolls. The raw percents were calculated and plotted from the 1965 data. The curve was smoothed by averaging the infestation of a specific week with the infestations of the prior and succeeding weeks and utilizing the resulting means as data points for the attempted curve fit.

Development Periods.—The methods for determining the development periods of the boll weevils infesting Arizona cotton were presented by Fye et al. (*12*) and Patana (*15*). The weevils were reared on cottonseed meal diet in petri plates from eggs extracted from wax-covered pellets of medium in which the females oviposited. The development periods were determined in environmental chambers at constant temperatures of 15°, 20°, 25°, 30°, and 35° C. and in programed temperatures representing cotton canopy temperatures with daily means of 25° and 30°.

Linear regression analysis of the reciprocal of 2-hour development on the logarithm of temperature for the constant temperature was performed. From this regression the accumulated reciprocal units of development for the programed temperatures were determined. These accumulated reciprocal units accurately estimated the development of the weevils in the programed regimes.

Temperatures.—Temperatures in squares and bolls were measured for 24 to 48 hours per week in short-staple (Acala) and long-staple cotton with thermocouples read by a 24-point recorder. Similar measurements were made at the soil surface. From the data obtained during these representative periods, regression equations were developed for estimating the temperatures in the squares, bolls, and on the soil surface from air temperatures (Fye *6*, Fye and Bonham *8–9*).

Period From Puncture to Drop of Punctured Square.—Between July 6 and 23, 1967, approximately 1,000 cotton squares were tagged within 24 hours after they were punctured by boll weevils. The dates on which they were tagged and on which they dropped from the plant were recorded. From these records the periods that the punctured squares remained on the plant were calculated and the distribution was plotted.

Mortality of Immature Weevils in Squares on Soil Surface.—Laboratory studies of the mortality of immature boll weevils in fallen cotton squares were conducted on thermostatically controlled sand tables. The periods necessary to cause mortality of the immature weevils were determined at several temperatures. A regression equation to estimate the percent mortality on the basis of a summation of time (1-hour period) × temperature in excess of 38° C. was developed by the least squares method (Fye and Bonham *8*).

Boll Maturation.—During the 1968 growing season daily temperature regimes in a field of Deltapine Smoothleaf cotton were under detailed study at weekly intervals. The air temperature was recorded continuously with a hygrothermograph in a standard weather instrument shelter. When the bolls began to open, the percent of open bolls was estimated from counts of bolls on 25 randomly selected plants. Similar counts were made in an adjacent field of long-staple cotton. The degree-days between the time of squaring (June 10) and the opening of the bolls were estimated by standard degree-day methods. Threshold temperatures of 13° and 38° C. were arbitrarily used in the estimates.[5] The percent of open bolls was plotted against the temperature input in degree-days.

Curve Fitting.—The following general models were utilized, when appropriate, in attempts to fit curves to the data points by the least squares method:

$$y = k_o(\ln x - k_1) \tag{I}$$

$$y = a + bx + cx^2 \tag{II}$$

$$\ln y = a + bx + cx^2 \tag{III}$$

$$y = a + bx + cx^2 + dx^3 \tag{IV}$$

$$y = a + b \ln x + c(\ln x)^2 \tag{V}$$

$$y = a_o + \sum_{i=1}^{n} a_i \sin i\, x \tag{VI}$$

$$y = a + b \arctan \frac{(x - 9.5)}{3} \tag{VII}$$

$$y = a + b(r^x) \tag{VIII}$$

All analyses included predicting a conditional

[5] H. N. Stapleton, professor, Department of Agricultural Engineering, University of Arizona, personal communication.

probability of an occurring event provided the time variable assumed a certain value. Recognition of problems encountered in deriving the theoretical models for these probability distributions led to the use of these general empirical models.

FECUNDITY AND OVIPOSITION

Subsystem OW (fig. 1)—Adult Female Populations.—Any population assessment method that defines the number of adult female weevils when squares become available as oviposition sites could be utilized for the initial population assessment. The method presented by Kuehl and Foster (*13*) has been suggested. Regardless of the method used, a confidence limit must be placed on the mean population estimate. The number of adult female weevils when squares become available is the first critical population in a given crop year. With properly developed models to predict the overwintering population and the subsequent survival, this assessment might not be necessary. However, until such models are developed, the assessment of the ovipositing population at the start of squaring is absolutely essential.

Subsystem OWE (fig. 1)—Oviposition and Fecundity.—The daily oviposition may be approached in two ways: In the first method, the number of females may be estimated and multiplied by the mean daily fecundity.

$$E_i = F_i\bar{E}$$

where

E_i = number of eggs laid daily

F_i = number of ♀♀ (females)

$\bar{E}$ = mean daily fecundity per ♀ (Fye *5*)

To estimate the number of females, the daily mortality and entry into the ovipositing population must be considered.

$$F_{i+1\,\ldots\,i+n} = F_{i\,\ldots\,i+n} - M_{i\,\ldots\,n} + N_{i\,\ldots\,n}$$

where

$F_{i+1\,\ldots\,i+n}$ = number of ♀♀ on successive days after initiation of oviposition on day i

$M_{i\,\ldots\,n}$ = number of ♀♀ dying each day

$N_{i\,\ldots\,n}$ = number of new ovipositing ♀♀ entering population each day

M may be estimated from the mortality curves for the overwintering population and the subsequent F_1 and F_2 generations of boll weevils from Avra Valley, Ariz., presented in figure 2. The curves were based on insectary data on longevity and fecundity (Fye *5*). The curvilinear model for the mortality curve of the overwintering weevils using the least squares method for estimating the coefficients was

$$\hat{y}_{mo} = 165.7\ (\ln i - 5.093) \qquad 172 < i < 305\ ^{6} \qquad \text{(a)}$$

where

$\hat{y}_{mo}$ = estimated percent mortality of overwintering population

i = time expressed in Julian calendar days [6]

The model for the combined F_1 and F_2 generations was

$$\hat{y}_{mf} = -26{,}971.9 + 9{,}677.1 \ln i - 864.9\ (\ln i)^2 \qquad 197 < i < 263\ ^{7} \qquad \text{(b)}$$

where

$\hat{y}_{mf}$ = estimated percent mortality of F generations

i = time expressed in Julian calendar days [7]

Fits were attempted with general models I, II, III, and V for the data points for overwintering populations and subsequent F generations. The equation resulting from model I was selected for the overwintering weevils because it provided the best correlation (r = 0.984) and the least standard error of the estimate (5.33). Model V provided the best fit for the equation pertaining to the F generations as indicated by the highest correlation coefficient (r = 0.978) and the smallest standard error of the estimate (6.38). Although the overwintering population curve exceeds 100 percent and the F generation curve moves downward at its extreme (fig. 2), they accurately estimate over 95 percent of the mortality.

In the second method of estimating the daily oviposition, the number of females emerging each

[6] Equation utilizes day 172 as starting date; 172 should be employed likewise for any utilization of this model.

[7] Equation utilizes day 197 as starting date; 197 should be employed likewise for any utilization of this model.

day and a known population oviposition pattern in time may be used.

$$E_i = \Sigma[NO\bar{E}]_{i\,\ldots\,n}$$

where

E_i = number of eggs laid daily

$N_{i\,\ldots\,n}$ = number of ♀♀ emerging each day $i \ldots n$

O = percent of total fecundity daily of overwintering or F population

$\bar{E}$ = mean lifetime fecundity per ♀ (Fye 5)

O may be estimated from equations developed from the oviposition data on the Avra Valley weevils presented in figure 3. The curves were developed from 1968 insectary data on longevity and fecundity (Fye 5). The linear model for the ovipositional pattern of the 1968 overwintering generation was

$$\hat{y}_{fo} = 19.3x - 0.8x^2 - 16.1 \qquad \text{(c)}$$

where

$\hat{y}_{fo}$ = estimated accumulative percent of eggs laid by overwintering population

x = number of weeks after emergence

Therefore,

$$E_w = (19.3x - 0.8x^2 - 16.1)_w E - (19.3x - 0.8x^2 - 16.1)_{w-1} E \qquad \text{(d)}$$

where

E_w = number of eggs laid during week w

x = number of weeks after emergence

E = total fecundity of overwintering ♀♀ population (or total ♀♀ × eggs per ♀)

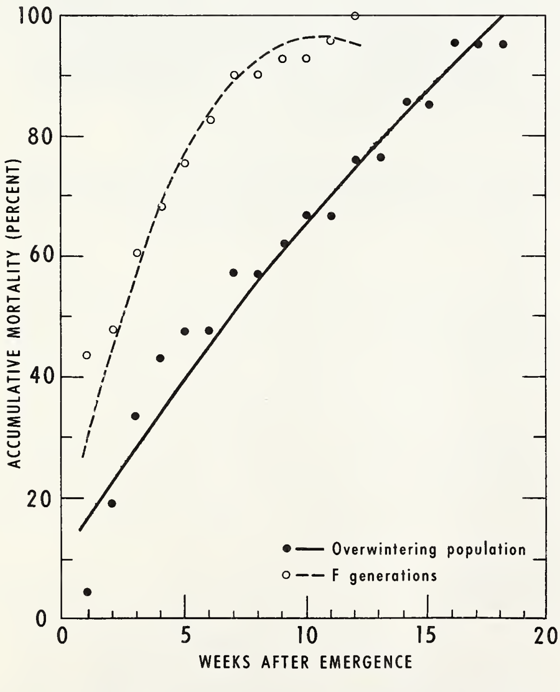

FIGURE 2.—Mortality curves for boll weevils from Avra Valley, Ariz., 1968.

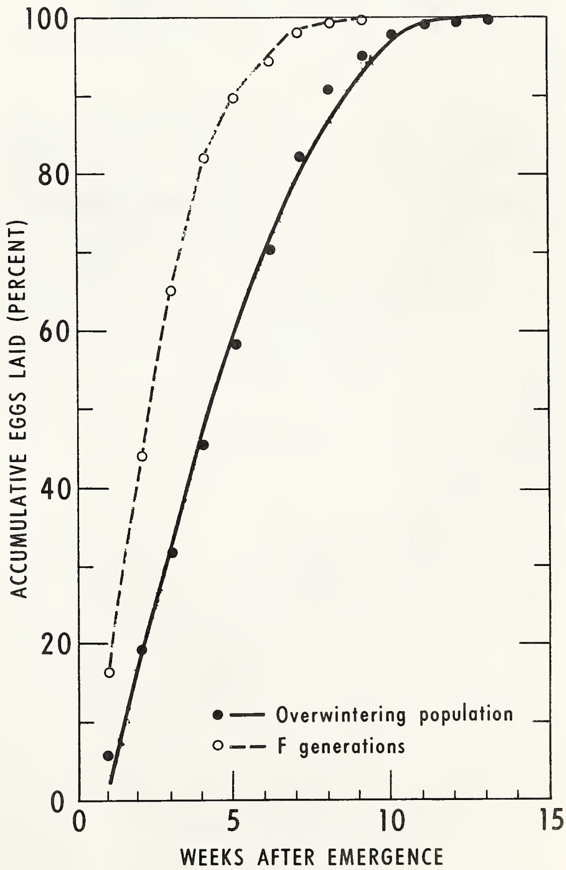

FIGURE 3.—Composite oviposition curves for boll weevils from Avra Valley, Ariz., 1968.

The model containing a cubic term in x for the subsequent generations includes the F_1 generations of 1966 and 1968, the F_2 generation of 1968, and the F_3 generation of 1966. The composite model is

$$\hat{y}_{ff} = -21.4+42.3x-5.0x^2+0.2x^3 \quad \text{(e)}$$

where

y_{ff} = estimated accumulative percent of eggs laid by F generation

x = number of weeks after emergence

Therefore,

$$E_w = (-21.4+42.3x-5.0x^2+0.2x^3)_w(E) - (-21.4+42.3x-5.0x^2+0.2x^3)_{w-1}(E) \quad \text{(f)}$$

where

E_w = number of eggs laid during week w

x = number of weeks after emergence

E = total fecundity of F generation (or total ♀♀ × eggs per ♀)

Models III and IV yielded the best fits for the oviposition data for the overwintering population and F generations, respectively. The correlation coefficients were 0.998 and 0.999 and the standard errors of the estimates were 2.49 and 0.98, respectively. Although the estimated accumulative oviposition exceeds 100 percent in the final part of the curve (fig. 3), 99 percent of the oviposition is accurately estimated. If we assume that a female weevil from cultivated cotton has a potential of 200 to 300 eggs (Fye *5*), the estimation equation predicts the oviposition accurately for all but four to six eggs.

Subsystems SB, S, and B (fig. 1)–Number of Eggs Laid in Squares and Bolls.—During the fruiting season the female may lay eggs in either squares or soft bolls. The percent of boll weevil egg punctures in squares and bolls in the 13 selected fields of 1965 is presented in composite form in figure 4. The smoothed data points pertaining to squares are presented in figure 5 for the fitted curve.

$$\hat{y}_{os} = 81.87-5.95 \sin x-1.39 \sin 2x +0.80 \sin 3x+1.07 \sin 4x +0.61 \sin 5x-3.27 \sin 6x -1.24 \sin 7x-1.14 \sin 8x +0.70 \sin 9x$$

where

$\hat{y}_{os}$ = estimated percent of egg punctures in squares

x = number of weeks > 4 after squaring commenced

Model VI gave the best correlation (r = 0.996) with nine terms. The standard error of the estimate with nine terms was 0.77. The fluctuations in the square and boll punctures were due to the changes in the fruiting pattern of the cotton plants. Whenever bolls of the proper age for puncture were present, the weevils shifted to them as oviposition sites, but as the bolls matured, the weevils shifted to the oncoming squares.

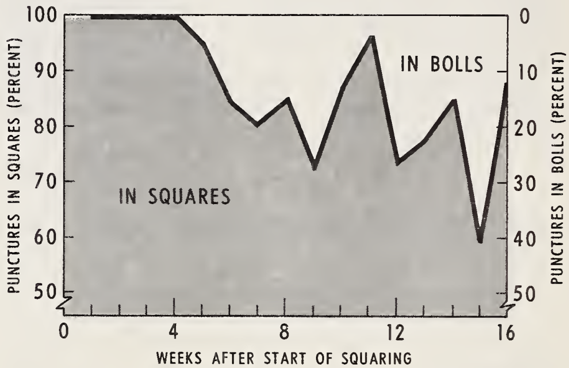

FIGURE 4.—Percent of boll weevil egg punctures in squares and bolls in 13 selected cottonfields in southern Arizona, 1965.

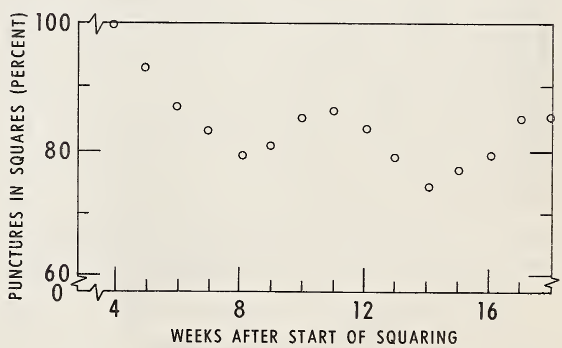

FIGURE 5.—Smoothed curve for boll weevil egg punctures in squares in 13 selected cottonfields in southern Arizona, 1965.

DEVELOPMENT (D SERIES)

Subsystems DS1 and DB1 (fig. 1)—Development Periods.—The simple linear model for the proportions or reciprocal units of boll weevil development based on the temperature of the substrate during each 2-hour period was presented by Fye et al. (*12*).

$$\hat{y}_{ru} = 0.01346 \log st - 0.01494 \qquad \text{(h)}$$

where

$\hat{y}_{ru}$ = estimated reciprocal units of development during 2-hour period

st = mean temperature (° C.) of substrate during 2-hour period

The summation of these reciprocal units represents the total development of the boll weevil.

$$\Sigma\hat{y}_{ru} = \sum_{p=1}^{n} \left[0.01346 \left(\log \frac{t_h + t_l}{2}\right) - 0.01494\right] = 1 \qquad \text{(i)}$$

where

$\hat{y}_{ru}$ = estimated reciprocal units of development

$p_{1 \ldots n}$ = necessary periods for development

t_h and t_l = high and low temperatures (° C.), respectively, of substrate during each 2-hour period

1 = total reciprocal units of weevil development

Subsystems DS2 and DS3 (fig. 1)—Temperatures in Squares.—Development of the egg and of part of the larval stage of the boll weevil is passed in either squares or bolls. Therefore, to establish the length of the development period, the temperatures in squares and bolls must be obtained.

The following equation for estimating the temperature in squares of short-staple (Acala) cotton from air temperatures was presented by Fye (*6*):

$$\hat{y}_{sq} = 6.2 + 0.80\ (at) \qquad \text{(j)}$$

where

$\hat{y}_{sq}$ = estimated temperature in squares of short-staple cotton

at = air temperature (° C.)

A similar equation for estimating the temperature in squares of long-staple cotton from air temperatures has been developed (Fye and Bonham *9*).

$$\hat{y}_{lq} = 3.1 + 0.84\ (at) \qquad \text{(k)}$$

where

$\hat{y}_{lq}$ = estimated temperature in squares of long-staple cotton

at = air temperature (° C.)

Therefore, the summation of the reciprocal units of development in short-staple cotton for 24 hours is

$$\hat{y}_{rus} = \sum_{p=1}^{12} \left[0.01346 \left[\log_{10} \frac{(6.2 + 0.80at_h) + (6.2 + 0.80at_l)}{2}\right] - 0.01494\right] \qquad \text{(l)}$$

where

$\hat{y}_{rus}$ = summation of reciprocal units of development for 24 hours

p_1 = first 2-hour period on given day

p_{12} = final 2-hour period on given day

at_h = high air temperature (° C.) during each 2-hour period

at_l = low air temperature (° C.) during each 2-hour period

A similar substitution of the regression equation for the relationship of air temperature to the temperature of long-staple cotton squares may be made if development of the boll weevil in long-staple cotton is under consideration.

Subsystem DS4 (fig. 1)—Period From Puncture to Drop of Punctured Square.—Cotton squares that have been punctured by boll weevils are usually not retained on the plant through the entire development period of the weevil. Data on the percent drop of the punctured squares are presented in figure 6.

The model for the accumulative percent drop was

$$\hat{y}_{dr} = 32.2 + 27.1 \text{ arc tan}^{8} \frac{(x-9.5)}{3} \qquad \text{(m)}$$

where

$\hat{y}_{dr}$ = estimated accumulative percent drop on given day after squares are punctured

x = number of days after squares are punctured

Sixty-five percent of the punctured squares dropped from the plant and the remainder developed into bolls. These data indicate that about 35 percent of the eggs failed to hatch and larvae were not present to feed and cause abscission of the square. Since daily temperatures exceeded 100° F. during the study, these eggs probably were killed by the high temperatures or by the rapid proliferation in the oviposition site.

Subsystem DS5 (fig. 1)—Temperatures on Soil Surface.—After the squares containing the immature forms of the boll weevil have fallen from the plant, the temperature in the squares approximates that of the soil surface. Fye and Bonham (*8*) presented several linear regression models for estimating soil-surface temperatures from air temperatures, e.g.,

[8] Arc tan is expressed in radians.

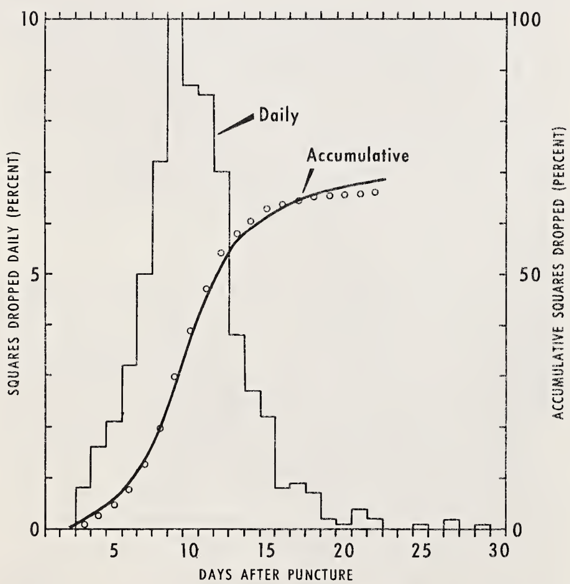

FIGURE 6.—Daily and accumulative percent drop of Deltapine Smoothleaf cotton squares punctured by boll weevil, Tucson, Ariz., 1967.

$$\hat{y}_{ss} = 23.5 + 0.5\,(at) \qquad \text{(n)}$$

where

$\hat{y}_{ss}$ = estimated temperature (° C.) of soil surface

at = air temperature (° C.)

Two relationships must be considered in regard to the immature weevils in the fallen squares on the ground. (1) Development: The summation of reciprocal units of the daily development temperatures may be made with the following equation:

$$\hat{y}_{russ} = \sum_{p=1}^{12} \left[0.01346 \left[\log \frac{(23.5+0.5at_h)+(23.5+0.5at_l)}{2} \right] - 0.01494 \right] \qquad \text{(o)}$$

where

$\hat{y}_{russ}$ = summation of 2-hour reciprocal units of development for 24 hours

p_1 = first 2-hour period on given day

p_{12} = final 2-hour period on given day

at_h = high air temperature < 38° C. during each 2-hour period

at_l = low air temperature < 38° C. during each 2-hour period

(2) Mortality: The mortality of weevils in the fallen squares is discussed in detail under subsystem MS2.

Subsystem DS6 (fig. 1)—Emergence of Adult Weevil.—Fifty percent of the weevils will emerge when

$$\Sigma\hat{y}_{rus} + \Sigma\hat{y}_{russ} = 1$$

where

$\Sigma\hat{y}_{rus}$ = summation of reciprocal units of development while square remains on plant

$\Sigma\hat{y}_{russ}$ = summation of effective reciprocal units of development while square is on soil surface

Subsystems DB2 and DB3 (fig. 1)—Temperature in Bolls and Its Relation to Boll Weevil Develop-

ment.—The temperatures associated with bolls must be considered in two respects. Early in the season the eggs laid in the bolls develop and the mature weevils are trapped within the boll until it matures and opens and thereby releases the adult weevils. In this respect, the effect of temperature on boll maturity must be considered. Later in the season the bolls fail to mature and the weevils contained in the bolls become the major part of the overwintering population.

The temperature for the development of boll weevils in bolls in short-staple cotton (Fye *6*) is

$$\hat{y}_{sb} = 4.7 + 0.86\ (at) \qquad \text{(p)}$$

where

$\hat{y}_{sb}$ = estimated boll temperature (short-staple cotton)

at = air temperature (° C.)

and in long-staple cotton (Fye and Bonham *9*) is

$$\hat{y}_{lb} = 1.8 + 0.89\ (at) \qquad \text{(q)}$$

where

$\hat{y}_{lb}$ = estimated boll temperature (long-staple cotton)

at = air temperature (° C.)

These equations may be substituted in subsystem DB1 (p. 7) to estimate the development of the weevils within the bolls.

Subsystems DB5 and DB6 (fig. 1)—Boll Maturation.—The boll maturation data are presented in figure 7.

The best equation for boll maturation and weevil release in short-staple cotton considering general models I–V (fig. 7) is

$$\ln \hat{y} = -22.93 + 0.016x \qquad \text{(r)}$$

where

$\ln \hat{y}$ = ln of estimated percent of open bolls

x = accumulated day-degrees > 55° F. after squaring starts

Therefore, boll maturation and subsequent weevil release commence after the temperature summation (fig. 7).

$$M_{sb} = \sum_{p=1}^{n} \left[\frac{(at_h + at_l)}{2} - 55 \right] = 1{,}940 \qquad \text{(s)}$$

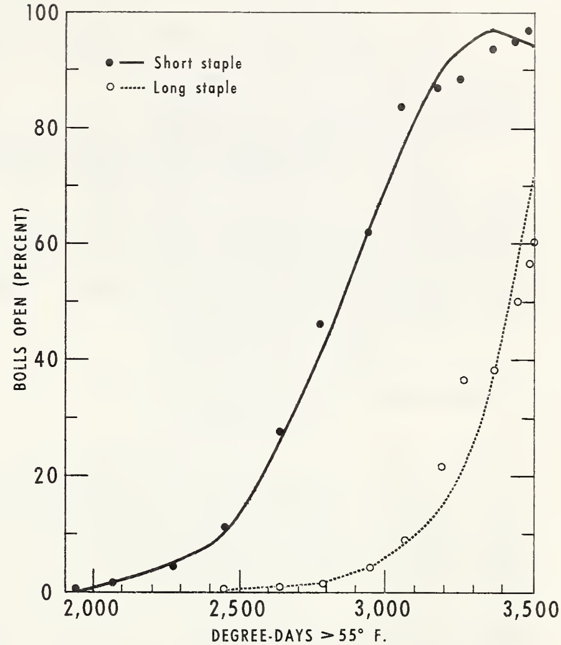

FIGURE 7.—Boll maturation in fields of Deltapine Smoothleaf short-staple cotton and of Pima S–2 long-staple cotton in relation to degree-days > 55° F. after squaring, Avra Valley, Ariz., 1968.

where

M_{sb} = temperature input in degree-days > 55° F. necessary to mature short-staple cotton boll

p_1 = day originating square was produced

p_n = day temperature input summation = 1,940 degree-days > 55° F.

at_h = high daily temperature

at_l = low daily temperature

Boll maturation and weevil release in long-staple cotton occur according to the equation (fig. 7)

$$\ln \hat{y} = 13.31 + 0.005x \qquad \text{(t)}$$

where

$\ln \hat{y}$ = ln of estimated percent of open bolls

x = accumulated day-degrees > 55° F. after squaring starts

or after the heat summation

$$M_{lb} = \sum_{p=1}^{n} \left[\frac{(at_h + at_l)}{2} - 55 \right] = 2{,}450 \qquad \text{(u)}$$

where

M_{lb} = temperature input in degree-days > 55° F. necessary to mature long-staple cotton boll

p_1 = day originating square was produced

p_n = day temperature input summation = 2,450 degree-days > 55° F.

at_h = high daily temperature

at_l = low daily temperature

These equations for boll maturation are based on the number of bolls present on October 1–14. The equations were the best based on the least squares fit of models II, III, and IV and were utilized because they provided the best correlation and the lowest standard error of the estimates. Obviously all the bolls present did not open and the precision of the fit deteriorates late in the season. This would be expected because the late-season heat input is inadequate to mature all the last bolls and these serve to harbor the boll weevils through the winter. The poor fit late in the season may be attributed to short periods of heat above the development threshold of the cotton. They cause poor maturation because of insufficient physiological activity. The lack of adequate heat input is further complicated by frosts and use of defoliants.

The heat input associated with the maturation of cotton bolls far exceeds that required for boll weevil development from eggs laid when the bolls are small. Therefore, we may assume that all the weevils will emerge when the bolls mature. The number emerging becomes a function of the total number of eggs laid in the bolls as the season progresses.

MORTALITY (M SERIES)

The subsystems pertaining to the development of boll weevils in Arizona cotton have been discussed with little regard for the concurrent mortality. This mortality is considered in the following subsystems.

Subsystem MS1 (fig. 1)—Mortality in Squares on Plant.—In the discussion of subsystem DS4 it was noted that 35 percent of the punctured squares failed to drop from the plant, indicating that the eggs were rapidly killed and abscission was not triggered. This is the result of a single test and further elaboration of the causes and extent of mortality of boll weevil eggs in squares will be necessary to properly estimate the egg loss.

Subsystem MS2 (fig. 1)—Mortality in Fallen Squares on Soil Surface.—At temperatures greater than 38° C. mortality of the immature boll weevils occurs (Fye and Bonham *8*), and the summation of the time and temperature in excess of 38° may be made.

$$X_{tt} = \sum_{p=1}^{n} [h\ e] \qquad \text{(v)}$$

where

X_{tt} = summation of 1-hour period × temperature > 38° C. during boll weevil development

$p_{1\,\ldots\,n}$ = periods in which mean temperature exceeds 38° C.

h = number of 1-hour periods in which temperature exceeds 38° C. by a specific e

e = temperature in excess of 38° C.

The soil-surface temperatures may be estimated from air temperatures with the equation presented in subsystem DS5 (p. 8) or from the more detailed regression analysis presented by Fye and Bonham (*8*). From this summation the mortality of the weevils in the fallen squares may be calculated with the model (fig. 8) presented by Fye and Bonham (*8*).

$$\hat{y}_{ms} = 4.84 - (2.36)\ (0.559\ X_{tt})\ (S_f) \qquad \text{(w)}$$

where

$\hat{y}_{ms}$ = ln of estimated percent mortality on soil surface

X_{tt} = summation of 1-hour periods × temperature > 38° C. during boll weevil development

S_f = number of fallen squares daily with boll weevil egg punctures

Thus from the development subsystems (DS) the time of emergence of the adult weevils from

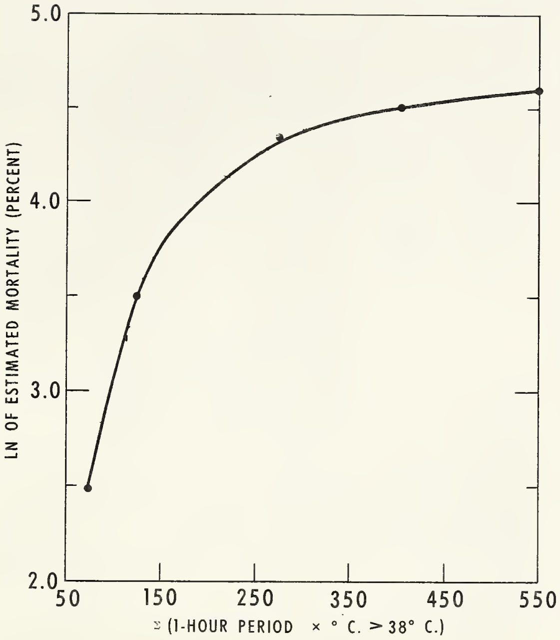

FIGURE 8.—Mortality of immature boll weevils in fallen cotton squares as function of time × temperature > 38° C.

squares may be estimated, and from the original number of eggs and the mortality subsystems (MS) the number of survivors emerging from squares can be estimated (fig. 1).

Subsystem MB1 (fig. 1)—Mortality in Bolls.—No valid estimates of the losses of boll weevil eggs laid in bolls are possible with available information.

DEVELOPMENT AND MORTALITY

Having developed preliminary subsystems from the available data, a composite series may be assembled utilizing the development and mortality sequences presented in figure 1. The first oviposition occurs when only squares are available.

$$[(♀_d \hat{y}_{fo} E_o) - m_{sq} - \hat{y}_{ms}]_{d\ldots n}(S_r) = ♀_{fd\ldots fn}$$

The system must be elaborated when bolls also become available and numbers of progeny are —
From squares

$$[(♀_d \hat{y}_{fo} E_o)(\hat{y}_{os}) - m_{sq} - \hat{y}_{ms}]_{d\ldots n}(S_r) = ♀_{fd\ldots fn}$$

From bolls

$$[(♀_d \hat{y}_{fo} E_o)(100 - \hat{y}_{os}) - m_{ll}]_{d\ldots n}(S_r) = ♀_{fd\ldots fn}$$

where

$♀_d$ = number of ♀♀ present on day squares become available for oviposition, i.e., ovipositing overwintering population

$\hat{y}_{fo}$ = percent of eggs laid by overwintering population each week after squares become available (for daily input, assuming linear oviposition during each week, use $\hat{y}_{fo}/7$) (equations c and d, p. 5)

E_o = mean fecundity of overwintering ♀ = 33 (Fye 5)

$\hat{y}_{os}$ = estimated percent of eggs laid in squares (equation g, p. 6)

m_{sq} = mortality in squares on plant (about 35 percent, see subsystem DS4, p. 7)

$\hat{y}_{ms}$ = mortality on soil surface (equation w, p. 10)

$d\ldots n$ = period of oviposition

S_r = proportion of ♀♀

$♀_{fd\ldots fn}$ = number of ♀♀ resulting daily from eggs laid in squares each day of oviposition period

m_{ll} = mortality in boll

For the purpose of properly determining the development and mortality of the immature weevils in the squares, the time of square drop from the plant must be estimated.

$$S_{dr} = \Sigma\left[\hat{y}_{dr}[♀_d]\left[\frac{\hat{y}_{fo}}{7} E_o\right]\right]_{d\ldots n}$$

where

S_{dr} = daily drop of squares punctured on given day

$\hat{y}_{dr}$ = percent of daily square drop (equation m, p. 8)

$♀_{d\ldots n}$ = number of ovipositing ♀♀

$\frac{\hat{y}_{fo}}{7}$ = percent of eggs laid by population on given day (equation d, p. 5)

E_o = mean fecundity per ♀

When the time of drop has been determined, the development from eggs laid on a given day may be estimated

In squares

$$\left[\sum_{i=e}^{y} \hat{y}_{rus} + \sum_{i=y}^{z} \hat{y}_{russ}\right] = 1$$

where

y = day of square drop after e

i = day summation starts

e = day of oviposition

$\Sigma\hat{y}_{rus}$ = reciprocal units of development while square is on plant (equation l, p. 7)

z = day of adult emergence after y

$\Sigma\hat{y}_{russ}$ = reciprocal units of development while square is on soil surface (equation o, p. 8)

1 = summation of reciprocal units of development required for weevil development and emergence

In bolls

The actual development of the weevil is

$$\sum_{i=e}^{z} \hat{y}_{rul} = 1$$

where

z = day when summation of reciprocal units of development = 1

i = day summation starts

e = day of oviposition

$\hat{y}_{rul}$ = reciprocal units of development in boll

However, the weevil cannot be released from the boll until the boll matures. Therefore release occurs when

$$M_{sb} \text{ (or } M_{lb}) - 550 \text{ degree-days} > 55° \text{ F.}$$
$$-175 \text{ degree-days} > 55° \text{ F.} \approx 1{,}200 \text{ (or } 1{,}725)$$

where

M_{sb} or M_{lb} = day-degrees required to mature short-staple or long-staple cotton boll after square formation

550 = estimated Σ of day-degrees > 55° F. from square formation to bloom

175 = estimated Σ of day-degrees for 5 days after bloom assuming boll is vulnerable to boll weevil puncture for 10 days after bloom fall and mean daily day-degree input during growing season (July–Sept.) is 25 day-degrees > 55° F.

Similar calculations can be made for the F generation by substituting $\hat{y}_{ff}$ for $\hat{y}_{fo}$ in the appropriate equations. The mean fecundity of 200 eggs per female presented by Fye (*5*) may be used as an estimate of E_o.

The development equations will estimate the mean day of emergence of the surviving progeny from eggs laid on a specific day, and the fecundity and mortality equations will provide an estimate of the number of surviving progeny (fig. 1). Thus a summation of the estimated female progeny entering the ovipositing population on each day will yield the number of females providing the subsequent egg input into the squares and bolls (subsystems S and B). A summation of the oviposition from all the females on each day provides the total number of eggs entering into subsystems S and B. Thus the recycling within the framework of the overall system may be initiated on a daily basis.

Sequential application of the models with temperatures throughout the growing season results in the characterization of boll weevil populations in Arizona. Ordinarily overwintering populations are small and the high temperatures of late June and July slow the development of the weevils (Fye et al. *12*) and result in high soil temperatures that cause major mortality and small populations (Fye and Bonham *8*). As the canopy of the cotton closes, the temperatures in the squares and bolls and on

the soil surface are reduced (Fye *6*, Fye and Bonham *8–9*) and boll weevil development and survival are facilitated. The improved developmental and survival conditions coupled with the emergence of the accumulated population in the bolls result in a larger ovipositing population to attack the small bolls produced late in the season. Thus the top crop frequently produced under Arizona grower practices is vulnerable to boll weevil attack.

DISCUSSION

The equations presented here are preliminary. For final equations additional data must be obtained. In each model in which an assumption was made to utilize the available data, a great deal of data and analysis will be necessary to provide the complexity required for predictive capability. When several sets of data were available, the variation in the equations was indicative of the differences that may occur when several sets of conditions are analyzed. However, the equations demonstrate the potential of analyzing the various factors affecting an insect population.

Tests of the series of equations against available field data indicate that mortality on the soil surface (subsystem MS2) is the key to low boll weevil populations in Arizona. The composite series adequately describes the population dynamics of boll weevils without considering a large number of variables. Actually a single variable has been analyzed, and the complexity attached to this major variable, temperature, demonstrates the difficulties attending an elaborate analysis of interactions affecting an insect population.

However, until the analysis of complex variables affecting an insect population is completed and the interactions are incorporated into quantitative models, the entomologist will be incapable of predicting insect outbreaks except in a gross manner. As data are assembled, analyzed, and incorporated into a complex model, the predictive capability of the entomologist will be improved to a degree that will enable effective prediction of insect outbreaks and accurately assess control efforts.

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